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OPERATING AND MAINTENANCE EXPERIENCE WITH A 6-KW WIND ENERGY CO--ETC(U)
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TECHNICAL NOTE

TN NO: N-1641

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TITLE: OPERATING AND MAINTENANCE EXPERIENCE WITH A 6-kW WIND ENERGY CONVERSION SYSTEM AT NAVAL STATION, TREASURE ISLAND, CALIFORNIA

AUTHOR: D. Pal

DATE: July 1982

SPONSOR: Naval Sea Systems Command

PROGRAM NO: S0829-01-561

NAVAL CIVIL ENGINEERING LABORATORY
PORT HUENEME, CALIFORNIA 93043

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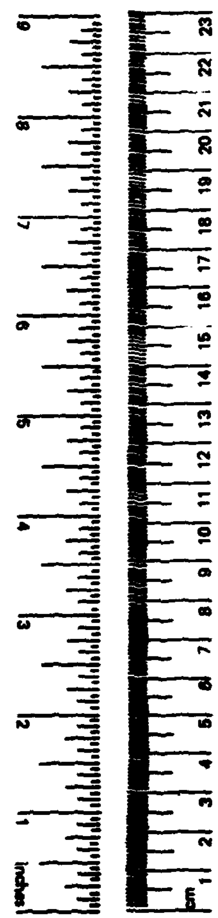
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

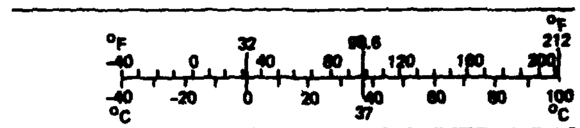
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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This report describes in detail the experience gained and lessons learned from the 6-kW grid-integrated Wind Energy Conversion System (WECS) demonstration at Naval Station, Treasure Island, San Francisco Bay. The objective of this demonstration was to develop operating experience and maintenance information on the 6-kW WECS using a combination of permanent magnet alternator with a line commutated synchronous inverter. The on-site

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measurements conducted during the demonstration indicate that the WECS site has annual average windspeeds of about 8 to 10 mph. The test results to date indicate a satisfactory performance of the WECS except for two failures involving arcing at the electrical terminals located on the yaw shaft. Due to wind characteristics encountered at the site, the performance data collected to date are at windspeeds of 20 mph or lower. For evaluating the WECS performance at all windspeeds, location at a windier site with annual average windspeeds of 14 mph or higher is recommended.

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This report describes in detail the experience gained and lessons learned from the 6-kW grid-integrated Wind Energy Conversion System (WECS) demonstration at Naval Station, Treasure Island, San Francisco Bay. The objective of this demonstration was to develop operating experience and maintenance information on the 6-kW WECS using a combination of permanent magnet alternator with a line commutated synchronous inverter. The on-site measurements conducted during the demonstration indicate that the WECS site has annual average windspeeds of about 8 to 10 mph. The test results to date indicate a satisfactory performance of the WECS except for two failures involving arcing at the electrical terminals located on the yaw shaft. Due to wind characteristics encountered at the site, the performance data collected to date are at windspeeds of 20 mph or lower. For evaluating the WECS performance at all windspeeds, location at a windier site with annual average windspeeds of 14 mph or higher is recommended.

CONTENTS

INTRODUCTION

As part of the Naval Civil Engineering Laboratory's (NCEL) ongoing investigation of the application of small Wind Energy Conversion Systems (WECS) to generate electricity at Naval shore installations, a grid-integrated 6-kW commercial wind plant was installed for demonstration at the Naval Station, Treasure Island, California, in September 1979. The tests being conducted during the demonstration are designed to yield data on the following:

1. Performance of a permanent-magnet-type wind-turbine-powered generator.

2. Interfacing characteristics of, and the quality of power delivered by, a 6-kW WECS using a single-phase synchronous inverter system.

3. Any design modifications required to improve the performance, operational features, and reliability of the system.

The system chosen for the demonstration includes an upwind, horizontal-axis, three-bladed, propeller-driven, 6-kW (at 28 mph) wind turbine with a variable-pitch rotor and a three-phase permanent magnet generator (alternator). The generator incorporates a rectifier which converts the variable voltage and frequency electricity produced by the variable speed rotor to DC electricity. The rectifier's output is connected to a 7.5-kW single-phase synchronous inverter which accepts the DC power from the rectifier, converts it to 60-Hz AC power, and feeds it into the grid network.

A 6-kW WECS size was chosen for the demonstration based on the premise that such a power level corresponds approximately to the peak electrical demand of a single family residence. Currently, in most commercially available WECS, horizontal-axis rotors (propellers) are utilized to drive an electrical generator through a step-up gearbox. Several vertical-axis wind turbines are available on the market and they afford certain advantages over the more conventional horizontal systems. However, between the two basic designs, propeller systems are by far more efficient for collecting wind energy. It is because of this wide disparity in efficiency that a turbine of horizontal axis design was chosen for the demonstration at Treasure Island. The upwind version of this design was chosen, thereby eliminating movement of the rotor blades into the tower's wake.

Because of the variable nature of the wind, the rotor of a horizontal-axis wind machine without any external controls will turn at variable speed. A generator driven by such a rotor will deliver electricity with variable voltage and frequency. The constant voltage and frequency electricity can be delivered by utilizing a wind turbine with blade-pitch controlled rotors designed to operate at constant speed. However, the power, and hence the total energy output, from such a

machine will be less than that delivered by a machine incorporating variable speed propellers, especially at locations where, most of the time, the prevailing windspeed is less than the rated windspeed of the wind turbine. As this may often be the case at most Naval shore establishments, a variable speed rotor was chosen for the demonstration to maximize the energy output of the WECS.

In several preceding demonstrations of WECS conducted by NCEL, self-excited generators have been used to convert mechanical energy in the wind into electrical energy. This demonstration uses a permanent magnet generator to eliminate use of a wound rotor and brushes. Such a generator design is free from problems inherent in these components (e.g., rotor winding failure due to excessive vibration, to overheating, or fatigue; or to brush failure due to excessive wear; or to corrosion due to the marine environment). One of the most important considerations in the choice of WECS configuration is the power conditioning method to be used. Among the various systems compatible with the 6-kW wind turbine installed at Treasure Island, a line-commutated and integrated synchronous inverter system was chosen for demonstration because of its availability, relatively low cost, and higher efficiency. The wind-turbine generator is mounted on an open truss, free standing, 60-ft-high tower. This tower design, which can be mass produced, was chosen for its reasonable cost and commercial availability.

SYSTEM DESCRIPTION

The WECS chosen by NCEL for demonstration at the Naval Station, Treasure Island, consists basically of an upwind 6-kW wind turbine and a synchronous inverter, both of commercial design. The wind turbine is comprised of a three-phase AC generator driven by a three-bladed rotor 17 feet 5 inches in diameter and is mounted on an open truss, free-standing tower 60 feet in height. At the time of installation, the WECS rotor diameter was 16 feet 5 inches (Rotor-1); new blades 6 inches longer than those originally installed were incorporated into the system in early December 1980 to increase the power production from the WECS. The rated windspeed of the turbine is computed to be about 28 mph. The system is currently set up to supply power for warehouse lighting and forklift battery charging. The modified rotor (diameter 17 feet 5 inches) is referred to as Rotor-2. A schematic drawing of the WECS demonstration at the Naval Station, Treasure Island, is given in Figure 1.

The wind turbine's rotor uses laminated wooden blades without twist. The nacelle housing the rotor shaft, gearbox, and generator is free to yaw about its vertical axis as directed by the wind's force. A tail arrangement located downwind of the WECS tower was provided to maintain rotor orientation into the wind. The cut-in speed of the machine is approximately 8 mph. Once the rotor starts to turn, its rotational speed is governed by the aerodynamic forces up to the turbine's rated windspeed of 28 mph. Beyond that point a governor system increases blade pitch with increasing windspeed to control rotor rpm's. At windspeeds in excess of the 45 mph furling windspeed, the tail is automatically rotated 90 degrees, which turns the rotor completely out of the wind.

The rotor drives a 3-phase permanent magnet AC generator through a standard step-up gearbox with a gearing ratio of 4.12. The generator incorporates a rectifier which converts the variable voltage and frequency AC power produced by the variable speed rotor to DC power. At the rated windspeed, the generator is designed to deliver 6 kW of DC power at 180 volts.

The DC electricity produced by the wind-driven generator is fed into a single-phase, line-commutated synchronous inverter. The inverter converts the variable DC voltage and power electricity to AC electricity at the grid line voltage and frequency. The principle of operation of a synchronous inverter is discussed in Appendix A. As shown in the schematic of Figure 1, the inverter accepts the rectified DC output of the generator, converts it to AC, and feeds it into the existing grid lines. The load connected in the grid network receives power at the voltage and frequency fixed by the grid lines. If, at any instant, the generator produces more power than is required by the load, the excess flows into the grid network. If the generator output is less than the load requires, the difference is provided by the grid.

In regard to quality of power, there are no rigid specifications for allowable total harmonic distortion for synchronous inverters operating with WECS. However, for WECS installations with the generator impedance properly matched to the impedance of the AC line, the total harmonic distortion of the output waveform is well within the range of typical loads encountered on utility lines at military installations. Although higher order harmonics in current waveform from the inverter at Treasure Island do exist and are as high as 11% (as in the case of the third harmonic), the fundamental amplitude contributes about 98% of the total power. Windworks, Inc. has published a complete harmonic analysis of the current waveform and more detailed descriptions of the features of the synchronous inverter being employed.*

Table 1 summarizes the aforementioned characteristics of the WECS installed at the Naval Station, Treasure Island, as well as presents some additional specific details of the system. An economic analysis based upon the method given in NCEL Technical Note N-1613** was performed for the 6-kW plant, and the results are given in Table 2. The data in Table 2 compares initial capital investment costs, differences in annual operating costs for wind-generated versus diesel-generated power, and differential life cycle costs and discounted payback periods, for Treasure Island and gives other sites potentially suitable for a 6-kW WECS installation of this type. Clearly, because of its relatively low wind potential, the Treasure Island location is not economically viable for such a WECS configuration.

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*Windworks, Inc. Information on Gemini synchronous inverter system. Mukwonago, Wisconsin.

**Naval Civil Engineering Laboratory. Technical Note N-1613: Wind power utilization guide, by D. Pal. Port Hueneme, Calif., Sep 1981, pp. 135-141.

TEST SITE, CONDITIONS, AND OBJECTIVES

The installation of the 6-kW WECS chosen for demonstration at the Naval Station, Treasure Island, was completed in September 1979. At the site, the prevailing wind direction is westerly, and average annual windspeed is estimated to be 8 to 10 mph (Table 2). Therefore, the average power available in the wind per unit disk area of the rotor is 4.5 W/ft^2 and the estimated annual output of the wind plant averages 3,000 kW-hours. The plant supplies a portion of the power for warehouse lighting and forklift battery charging. The map in Figure 2 shows the location of Treasure Island in relation to the San Francisco Bay area. Figure 3 shows the location of the WECS Treasure Island in the San Francisco Bay. Figure 4 shows the WECS installation adjacent to the supply department warehouse at the Naval Station.

Since the development of small WECS is at such an early stage, the main thrust of testing conducted to date and that being conducted at the present time has been directed toward the collection of system performance, operating, and maintenance data. The various types of data being collected on a periodic basis at the WECS demonstration site can be found in the Discussion section of this document.

INSTRUMENTATION

This Section describes the data collection instruments being used in the WECS demonstration at Treasure Island. A connection diagram showing the relative location of the various instruments in the system is given in Figure 5. Various instruments are described in detail in the material that follows.

Anemometer

The anemometer being used in the demonstration is the Bendix Aerovane Wind Transmitter, Model 120. It is a dual purpose instrument for measuring both windspeed and direction.

Windspeed is measured by a three-bladed impeller fastened to the armature of a tachometer magneto located in the nose of the instrument. The voltage generated by the magneto, a function of the windspeed, is electrically transmitted to a remotely located voltmeter which is calibrated to indicate windspeed in miles per hour for visual observation.

Wind direction is measured by a streamlined vane coupled to the rotor of a type 1 HG synchro. This synchro electrically transmits the vane position to a remotely located companion synchro which moves a pointer on a wind direction dial. Windspeed and direction are displayed on the Bendix Model 135 Aerovane Indicator. This type of instrument must have a 60-Hz power supply for its operation.

Indicator

The Model 135 Bendix Aerovane Indicator being used in the demonstration is an electrical device designed to provide constant visual indication of windspeed and direction. The indicator is used in conjunction with

the transmitter which furnishes the windspeed and direction inputs. It is mounted in a rack along with several other data collection instruments as shown in Figure 6. The indicator displays windspeeds in the range from 0 to 100 mph with an accuracy of ±1% and a threshold of 2 mph or less, depending on the sensor. The indicator displays wind direction in the range from 0 to 360 degrees with an accuracy of ±3 degrees and a threshold of 3 mph or less, depending on the sensor.

Following passage of the AC signal through the indicator, the signal passes through a conditioner which converts it to DC and enlarges it for use in the Autodata Nine and analog-to-digital data logger.

Autodata Nine Data Acquisition System With Averaging Option

This Autodata Nine System is an analog-to-digital data logger which has the capability of taking nearly continuous (several per second) measurements of desired phenomena on up to 256 channels and, following the conclusion of a predetermined period of time, calculating and recording the arithmetic average of the total number of measurements taken on each selected channel. Items being recorded for the demonstration at Treasure Island include speed and direction of the wind, generator output, and power supplied to the grid. Because of the random nature of wind, the windspeed, generator output, and power flow to the grid are averaged over a specified time interval, ranging from 15 minutes to 1 hour, to facilitate data analysis.

RS 232 Tape Recorder

An RS 232 tape recorder is incorporated in the System to store all collected data on magnetic tape. If desired, the data can be fed to a computer to construct plots for graphic displays.

Wattmeters

As shown in the wiring diagram (Figure 5), there are two wattmeters being employed in the demonstration at Treasure Island to collect the data specified in the test objectives. The meter in the line between the generator and the inverter measures the DC power supplied to the inverter by the generator. The meter between the inverter and the grid network measures the AC power supplied to the grid by the inverter. Both meters are watt-hour and wattmeter types utilizing Hall-effect power transducers as input elements. The watt-hour indications are based on the absolute volts and amperes. The specifications for the two wattmeters are presented in Table 3.

TEST RESULTS

Since installation in September 1979 at the Naval Station, Treasure Island, WECS performance has been generally satisfactory. Only two critical failures (system producing very little or no electrical power) due to component failure have occurred -- the first in late December 1979 and

the second in late March 1981. In both cases the failure was the result of generator output terminals being grounded through the tower. The insulation between a generator terminal and the generator body became weak due to marine salt deposition which resulted in a flashover. The generator terminal was grounded through the tower and only two, instead of three, phases were producing power, thus greatly reducing the system's generator power output.

In addition to these two critical failures, the only other technical problem encountered during the demonstration has been maintaining the synchronous inverter in a properly programmed state. Proper programming of the synchronous inverter involves setting the firing sequence of the silicon-controlled rectifiers to match the ambient wind conditions experienced at the site. When windspeeds are highly variable, maintaining the impedance of the WECS so that it is properly matched with that of the AC line is a chronic problem which must be frequently addressed.

Details of field data and WECS operation record for the period ranging from December 1979 through June 1981 are given in Appendix B. In particular the data tabulation shows the amount of AC energy into the grid and the amount of DC energy being generated by WECS. Also, the tabulated information contains average watt-hours per day being generated by WECS and the amount flowing into the AC grid, including the average efficiency of the inverter system based upon the average power level values. For reference, the test experience comments by the personnel monitoring the WECS installation at Treasure Island are also included in the table. In summary, during the period 10 December 1979 through 19 May 1980 system performance was extremely poor. As is evident from the field data log during this 162-day interval, only 5 kW-hr of AC and 112 kW-hr of DC power were produced, which corresponds to an efficiency of about 2% to 6% for the inverter. This poor system performance was due to the synchronous inverter being improperly programmed. After reprogramming of the synchronous inverter during the period 20 May through 23 May 1980, performance improved significantly.

For the period 20 May 1980 through 10 March 1981 (295 days), a total of 1,115 kW-hr of AC and 1,430 kW-hr of DC energy production were measured at the inverter and the generator output points, respectively. These energy production values correspond to annual outputs of 1,380 and 1,769 kW-hr for the two subcomponents of the WECS, respectively. The inverter efficiency during this period ranged between 75% to 81%.

At some time during the period 10 March through 13 April 1981, one of the generator terminals grounded to the tower (one of the aforementioned critical failures) and performance degraded significantly. The inverter efficiency dropped from a level between 75% to 81% down to 25%; and before the damaged generator terminal wire could be repaired on 19 May, it had dropped to less than 1%. Following repair of the system, the generator output returned to the normal level except for the inverter efficiency which ranged between 34% to 55% only. Apparently, the grounding of the generator terminals caused component failures in the inverter. In the 43-day interval from 19 May to 30 June 1981, about 172 kW-hr of AC and 340 kW-hr of DC power were measured at the generator and the inverter output points, respectively. These values reduce to annual outputs of 1,460 and 2,886 kW-hr, respectively.

DISCUSSION

This section discusses the data analysis results for the test objectives listed earlier. Because collecting data on some of the test objectives was not possible, the results of visual observations were substituted in the drawing of conclusions.

Climatological Data

Windspeed and Direction. Instantaneous readings of windspeed and direction are being made at time intervals of 0.01 second throughout the demonstration. Average values of windspeed and direction are computed over a period of 15 minutes, 1 hour, and 24 hours, respectively, using the Autodata Nine Data Acquisition System. Based upon the data analysis to date it was estimated that the annual average windspeed at the site is in the 8- to 10-mph range, with the predominant wind direction being from the West.

Ambient Air Temperature. Seasonal variation in air temperature for the San Francisco Bay area normally ranges from 40° to 80°F. This corresponds to about 8% change in air density throughout the year which is not significant enough to affect the power output computations for the machine.

Salt Concentration. No direct measurements were made to estimate salt concentration in the air. However, upon examination of the WECS tower surfaces no significant rust or corrosion were found. Hence, the corrosion potential at the site is not very severe.

Operating Data

Rotor. Influence of the following on rotor performance were noted:

1. Aerodynamic flutter. Since the rotor blades were constructed of solid wood, no aerodynamic flutter of the blade surfaces has been observed.

2. Gyroscopic forces due to sudden yawing. Gyroscopic forces were observed during heavy gusting winds, but were not significant enough to cause any problems. The installation of a commercially available automatic balancer on the rotor appears to dampen the gyroscopic rocking of the rotor.

3. Centrifugal forces. No unusually high centrifugal forces have been observed that would cause any damage to the system, including the blade attachment points.

4. Rotor-tower dynamic interaction. The natural frequency of the tower (1.5 Hz) is significantly less than the rotational speed range (1.67 to 3.33 Hz) of the rotor. Hence, no adverse rotor-tower dynamic interaction has been observed.

In addition, effect of blowing sand, dust, and salt air were considered. The pitching mechanism for the blades did experience some corrosion of the bearing surfaces due to the salt air. However, due to the body of water surrounding Treasure Island, no blowing sand and dust have been encountered at the WECS site.

Level of acoustical noise emission appears to be minimal (below 75 decibels). No effect upon Naval operations in nearby buildings was noted.

Drive System. Friction in the gearbox has not caused overheating or failure of its components. Temperature did not seem to affect drive system performance, and no significant problems were noted. However. no attempt was made to record temperature of the gear box oil.

Electrical Generator.

1. Output versus windspeed characteristics. The plots of power output versus windspeed, based upon the manufacturer's information and as measured in the field, are given in Figure 7. As pointed out in the Section on "System Description," the turbine's rotor diameter was increased from 16.417 (Rotor-1) to 17.417 feet (Rotor-2) in early December 1980 by installing new blades each 6 inches longer than the earlier set. The data points are plotted for the two rotors. The WECS performance data are presented in Tables C-1 and C-2 of Appendix C. It is evident from the plots of Figure 7 that increased rotor diameter resulted in higher power output and in reduced cut-in speed for the WECS.

2. Interaction of generator with control system and rotor dynamics. Control system has feathered the blades properly during high winds to effectively regulate power input to the generator.

3. Electrical and aerodynamic losses. Generator efficiency is measured by dividing generator output (DC) by available power in the wind. Using the data given in Table C-1, average generator efficiency for Rotor-1 ranged from about 18% to 35% as the windspeed values varied from 6.35 to 20.59 mph. The generator efficiency for Rotor-2, on the other hand, ranged from about 23.16% to 43.64% using the data collected in the 9-day period as the windspeed values ranged from 6.36 to 14.3 mph (Table C-2). Rotor-2 was found to be more efficient than Rotor-1.

4. Overload and overspeed characteristics. No overload condition has been observed. The control system has been effectively regulating the input power to the generator.

5. Short and no load effects on the generator operation. The shorting of generator terminals several times during demonstration did not cause any failure of the generator system. The generator has performed well under no load conditions over short intervals of time.

6. Effect of temperature, humidity, salt deposition, and water on the various connections and on performance. Salt deposition weakened the insulation around the electrical terminals located on WECS vertical shaft, thus grounding the generator to the tower. The power output of the generator was greatly reduced since only two instead of three phases were generating power.

7. Quality of power; i.e., the extent of harmonics generated. The current and voltage waveforms of the power from the WECS are shown in Figure 8. Due to the nature of the current waveform, some of the harmonics are fed into the power distributing system. However, the warehouse electrical system at the WECS site has not experienced any problems due to the presence of harmonics in the line.

Controls.

1. Sensitivity and stability of controls to windspeed and direction and rotor rotational speed. The controlling of the rotor rotational speeds under the load and beyond rated power point has been successful to date. The rotor blades have properly feathered during periods of windspeeds above the rated speed of the machine (28 mph). Additionally, the control mechanism responsible for automatically turning the rotor out of the wind, by rotating the tail 90 degrees, has functioned effectively during periods of extreme windspeeds above 45 mph and during no-load conditions.

2. Effect of temperature, humidity, and dust on operation. The operation of the control system has not been adversely affected by temperature, humidity, or dust to date.

3. Starting (cut-in), restarting, and shutdown including full or partial feathering characteristics. Excellent.

4. Simplicity and reliability of control system design. The control system has functioned properly so far with no recorded failures.

Tower.

1. Isolation of resonant frequency to minimize rotor-tower interaction. The natural frequency of the tower (1.5 Hz) is significantly less than the rotational speed range of the rotor (1.67 to 3.33 Hz).

2. Ease of installation. Erection of the tower was relatively easy, requiring only 2 men and use of a crane.

3. Tower shape and appearance. No complaints regarding the appearance of the generator-tower configuration at the site have been received.

4. Cost data. The free standing tower selected for this demonstration is about 60% more expensive than the guy wire type of tower used at some sites.

5. Tower stability. The stability of the tower during high winds has been good with no adverse shaking observed.

Synchronous Inverter.

1. Interfacing characteristics of synchronous inverter with permanent-magnet-type generator. No significant problems encountered thus far. Impedance matching is extremely important to optimize power conversions with varying windspeeds.

2. Efficiency and electrical losses. The inverter efficiency is computed by dividing the inverter output by the generator output. For Rotor-1, the inverter efficiency varied from about 63.8% to 83.6% (Table C-1) whereas with Rotor-2, the efficiency values varied from 70% to 79% (Table C-2). Generally, the inverter efficiency improved with Rotor-2.

3. Quality of power output. Typical grid voltage and current waveforms present at the output terminals of the synchronous inverter are shown in Figure 8. The inverter has not produced any significant distortion of the grid voltage waveform. The current waveform, however, does contain harmonics. The harmonic content of the current waveform recently analyzed for this type of inverter* concluded that, although higher order harmonics may exist and may be as high as 11% in the case of the third harmonic, the first harmonic contributes, on the average, 98% of the total power being transferred.

4. Interference (both electrical and electromagnetic) with the grid. None reported so far and no measurement was made to assess EMI effects.

5. Design capable of optimum conversion of wind power. Not enough performance data at higher wind speeds to evaluate this element of the test objectives.

6. Relative ease of interfacing with Station grid. No problems encountered so far.

Maintenance Data

Rotor.

1. Adequacy of bonds and fasteners and the blade's attachment connection to the rotor hub. The modified hub assembly Rotor-2 installed with the new blades contains better bonds and fasteners than the original design. Power to the rotors has presented no problems to date. Both rotors utilized laminated wood blades.

2. Blade fatigue cracks. No visible cracks. No X-ray type inspection was conducted.

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*Windworks, Inc. op. cit.

3. Resistance to corrosion of various components. The environment at Treasure Island is moderately corrosive in nature. The rotor components appear to offer good resistance to the environment at Treasure Island.

4. Ease of repair or replacement of various components. Disassembly of the modified hub does not pose any problems. Slip fit connections replace the original press fits to enable easier dismantling of components in the field.

Drive System.

1. Lubrication and servicing requirements. The lubricating oil must be changed every 6 months.

2. Ease of replacement or repair. No repairs were required.

Controls.

1. Lubrication and servicing requirements. Inspect system components and lubricate every 6 months.

2. Ease of replacement or repair. No repairs were required.

3. Blade pitching mechanism adjustment requirements. Improvements in the blade pitching mechanism constitute the major modification made to the hub assembly. Thus far, only the initial adjustment made during installation has been required. The oil filled hub assembly in Rotor-2 does cause oil leaks when the rotor is turning.

4. Checking of overspeed and feathering system, cut-in/cut-out system, and rotor lockout for servicing. Must be checked every 3 months.

Electrical Generator.

1. Maintenance of the connections, such as slip rings and generator terminals. During the test period the insulation washers surrounding the generator terminals had to be replaced. The salt air environment weakened the original insulation, allowing a short circuit to the tower to develop, which resulted in the two critical system failures.

2. Lubrication and servicing requirements of the bearings. Frequent lubrication of the bearings is not necessary. However, some lubrication problems exist in the bearings of the rotor blade pitching mechanisms. These problems are caused by infrequent operation of these components because the blades feather only when prevailing windspeed is equal to or greater than the WECS rated speed.

3. Accessibility and ease of repair or replacement. No repairs required so far.

4. Long-term integrity of connections and windings. Good.

Tower.

1. Adjust generator holding clamp. No adjustments have been required.

2. Protection against corrosion of various components of the tower. Good.

Miscellaneous.

1. Maintenance of adequate lightning protection. None required at Treasure Island site.

Reliability, Maintainability, and Availability Data

Number of Critical Failures. Those times when the system produced very little or no electrical power due to component failure, to date, have only occurred twice, resulting in critical failures. Both failures were caused by a corroded insulation washer on the yaw bearing electrical terminals, thus allowing one of the three phases of WECS to become grounded to the tower.

Times Before Critical Failure. To date, times before each failure are approximately 120 days and 460 days. This gives a mean time between failure (MTBF) of 290 days for the overall system.

Times to Repair.

1. Logistic time was the sum of time intervals during which the WECS was not capable of providing electrical power because one or more needed parts had to be obtained from outside sources. Typically, replacement parts such as rotor bearings and inverter required 3 to 4 weeks for their delivery.

2. Awaiting outside help time was the sum of time intervals during which the WECS was not capable of providing electrical power because outside assistance was required. The total time required to make travel arrangements for travel to Treasure Island averages about 2 to 3 weeks. Based upon this, a good estimate of time for providing outside help at the site was about 2 to 3 weeks.

3. Administrative time was the sum of time intervals during which the WECS was not capable of providing electrical power and no corrective maintenance was being performed. Whenever a problem with the WECS at the site was discovered, the personnel at the Station notified NCEL within 5 days.

4. Corrective maintenance time was the sum of time intervals during which repair, part replacement, alignment, or adjustment was undertaken in order to correct a failure, and the WECS was not capable of providing

electrical power. Mean time to repair (MTR) was defined as the arithmetic average of all corrective maintenance times. The corrective maintenance performed at the site required an average of 2 to 3 days for completion. For example, the installation of the modified rotor assembly with the longer blades required only 2 days of field work.

Availability. Availability was defined as the probability that the WECS would be capable of providing electrical power at any random point in time. It was calculated as:

$$A = \frac{\text{Uptime}}{\text{Uptime} + \text{Downtime}}$$

The value of availability A computed from the field tests for the WECS at Treasure Island is about 0.65. A good WECS installation must have A close to 0.95. The test and evaluation nature of the WECS setup at Treasure Island is partly responsible for a low availability. However, future tests will be directed at establishing this parameter for the WECS.

Power Output Data

Generator Efficiency. The WECS performance was measured during three separate test periods. The first two tests evaluated the WECS with Rotor-1 before installation of the new rotor assembly with the longer blades of Rotor-2. Average generator efficiency for these periods varied from 18% to 35%. The final test period evaluated the WECS with Rotor-2, and the test results indicate that the generator efficiency, depending upon the windspeed, ranged between 23% to 43%.

Synchronous Inverter Efficiency. This performance parameter was also computed based upon the field measurements taken during the test periods and the results are described in the Operating Data section on the synchronous inverter.

Overall System Efficiency. The overall system efficiency is defined as the product of the generator efficiency and inverter efficiency. The WECS overall system efficiency with Rotor-1 varied from 11.7% to 28.07% (Table 4). The values of overall system with Rotor-2 ranged from 16.6% to 32.07% (Table 5). Hence, the overall system improved with Rotor-2, and the WECS efficiency increased with the increase in windspeed.

Instantaneous Power Output of the WECS. The WECS power output as a function of windspeed, based upon manufacturer's information, is plotted in Figure 7 as a solid line. The figure also shows the data points from the field tests of the WECS with points from the original design (Rotor-1) and the longer blade design (Rotor-2), respectively. The data collected during the tests are up to windspeeds of 18 mph. The WECS power levels with Rotor-1 are in agreement with manufacturer's curve. The power output from WECS increased by 10% with Rotor-2.

Long-term Output of the WECS. During the 295-day period ranging from 20 May 1980 to 10 March 1981, about 1,115 kW-hr of AC power were generated by the WECS. If extrapolated linearly this represents an annual rate of 1,380 kW-hr. Since the windy period at Treasure Island extends from March through July, this extrapolation is not realistic. A practical WECS installation of the Rotor-2 design at Treasure Island is capable of producing about 3,300 kW-hr annually.

Summary of Performance

WECS performance with the two rotors is summarized in the following table:

Rotor Diameter (ft)	Period	Average Generator Efficiency (%)	Average Inverter Efficiency (%)	Average System Efficiency (%)
16.417	7-15 Jun 1980	21	78	16
16.417	2-3 Dec 1980	30	78	23
17.417	27 Dec 1980 - 4 Jan 1981	34	76	26

CONCLUSIONS

1. All the data on WECS performance at Treasure Island are taken at windspeeds below 20 mph (Figure 7). Since the WECS installation in September 1979, its performance has been satisfactory. Only two critical failures, where the system produced no electrical power due to component failure, have occurred. The first failure occurred in late December 1979 and the second in early April 1981. Each failure was caused by the arcing at electrical terminals located on the yaw shaft of the generator which resulted in grounding of the generator to the tower.

2. The operating times before failure have been approximately 120 days and 460 days, which correspond to a system MTBF of 290 days.

3. The only other technical problem encountered during the demonstration has been difficulty in keeping the synchronous inverter properly programmed to match its impedance with that of the generator at all windspeeds. For optimum performance of the WECS it is extremely important to match its impedance to that of the AC line at all windspeeds.

4. Between 20 May 1980 and 10 March 1981, a 295-day interval, 1,115 kW-hrs of AC and 1,430 kW-hrs of DC power were supplied by the WECS and generator, respectively. These values correspond to annual outputs of 1,380 and 1,769 kW-hrs, respectively. The inverter efficiency during this period ranged between 75% and 81%.

RECOMMENDATIONS

1. A more efficient means of maintaining the synchronous inverter in a properly programmed status needs to be devised. The WECS performance has not been very good during periods in which the inverter was not programmed properly, and sometimes these periods of poor performance have extended for several weeks before it was realized that a problem existed.

2. All of the test data for WECS performance at Treasure Island were taken at windspeeds below 20 mph. To measure WECS performance at higher windspeeds, it must be moved to a site with an annual average windspeed of 14 mph or more.

Table 1. Specific Details on the 6-kW WECS Demonstration at Treasure Island

Item	Detail	Description	
Wind Turbine Generator			
Propeller	Type	Rotor-2	Rotor-1
	Number of blades	3	3
	Diameter	17 ft 5 in.	16 ft 5 in.
	Circular area swept by blades	238.3 ft^2	211.7 ft^2
	Projection of blades on swept circular area		
	Aerofoil area density	5.2%	5.2%
	Rotational speed	100-200 rpm	100-200 rpm
	Rated windspeed	28 mph	28 mph
	Cut-in windspeed	8 mph	9 mph
	Furling windspeed	45 mph	45 mph
	Location with respect to tower	Upwind	Upwind
	Rated power coefficient	0.256	0.256
Gear Box	Type	Gear	
	Gear ratio	4 to 12	
Generator	Type	Three-phase permanent-magnet rotor	
	Number of poles	16	
	Rotational speed	412-824 rpm	
	Output frequency	DC	
	Rated voltage	140 volts	
	Rated power output	6.75 kW	6 kW
Tower	Type	Open truss, free-standing	
	Height	60 ft	
Power Conditioning Equipment			
	Type	Single-phase, line-commutated inverter	
	Rated voltage	120 volts AC	
	Rated power output	7.5 kW	
Site Wind Characteristics			
	Annual average wind speed, mph	8-10 mph	
	Average available power in the wind	4-5 watts/ft^2	

Table 2. Economic Analysis for the WECS With a Rating of 6 kW at 28 mph at Various Naval Sites

Items	Sites					
	Treasure Island	San Nicolas Island	Adak	Grand Turk	Kaneohe Bay	Opana
Annual average windspeed, mph	9.0	11.4	13.9	15.9	12.0	16.8
WECS annual output, kW-hr	3,000	7,500	10,800	13,800	7,800	15,700
Capital cost of WECS, $K	14.0	14.5	15.0	15.0	15.0	15.0
WECS operations & maintenance annually, $K	0.50	0.60	0.60	0.60	0.60	0.60
<u>Diesel-Generated Electrical Costs</u>						
Fuel, mills/kW-hr	-	90	90	90	-	-
Annual operations & maintenance, $K	-	0.70	0.70	0.70	-	-
Purchased electricity cost per kW-hr, mills	80	-	-	-	90	90
<u>Costs Displaced by WECS Annually, $K</u>						
Fuel or purchased electricity, $K	0.24	0.68	0.97	1.24	0.70	1.41
Operations and maintenance	-	0.1	0.1	0.1	-	-
<u>Economic Comparison</u>						
Differential life cycle cost, $/MBtu	-0.02	0	-0.0022	-0.0034	-0.0037	-0.0021
Discounted payback period, yrs (economic life of WECS = 25 yrs)	no pay back	25 years	11.7	8.0	no pay back	9.8

Table 3. Specifications for the Two Wattmeters Used in the WECS Installation

Item	DC Wattmeter	AC Wattmeter
Model	WH-7 Series 34 Ohio Semi-tronics	WH-3 Series 65 Ohio Semi-tronics
Input		
Current, normal	200 A maximum, 2 x rating	100 A maximum, 2 x rating
Voltage, normal	120 volts maximum, 1.25 x rating	240 volts maximum, 1.25 x rating
Phase, wire	DC phase, 2 wire	3-phase, 4 wire
Outputs (signal)		
Power	8 volts DC = 25 kW	7.5 volts DC = 80 kW
WH pulses	819.2/W-hr	204.8/W-hr
Electromechanical counter	10 W-hr/count	10 W-hr/count

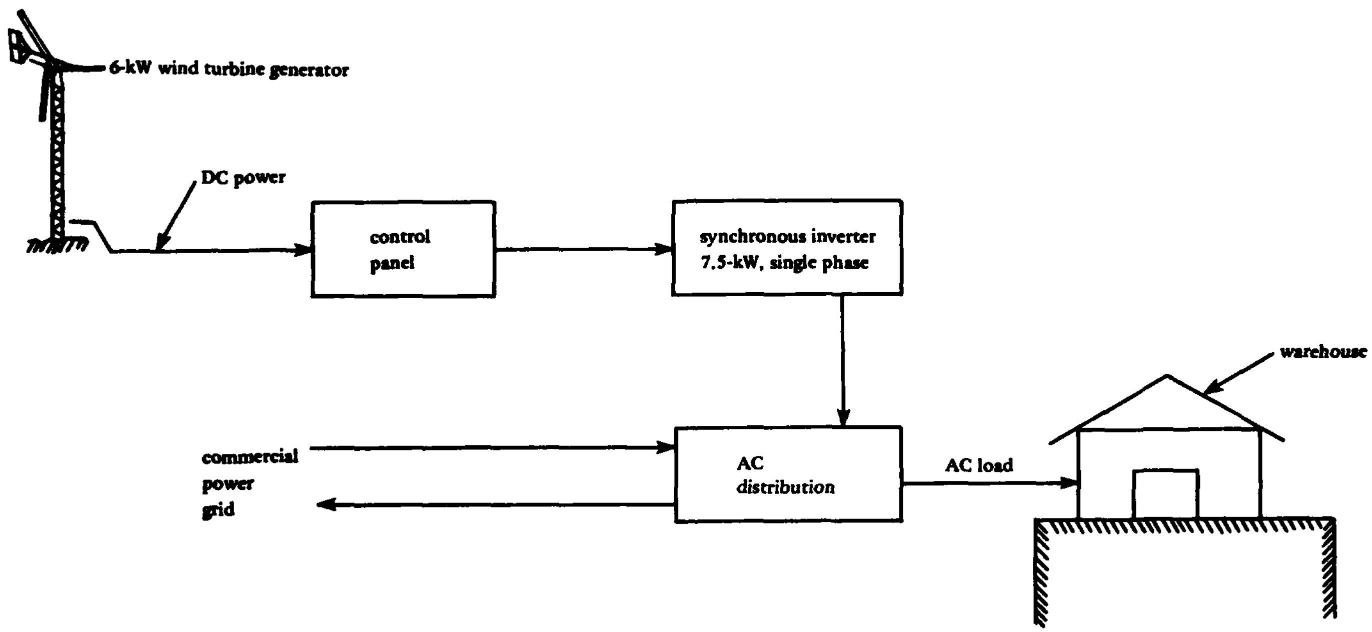

Figure 1. A schematic of the 6-kW wind plant with a single-phase synchronous inverter facility integrated with a warehouse power supply at Naval Station, Treasure Island.

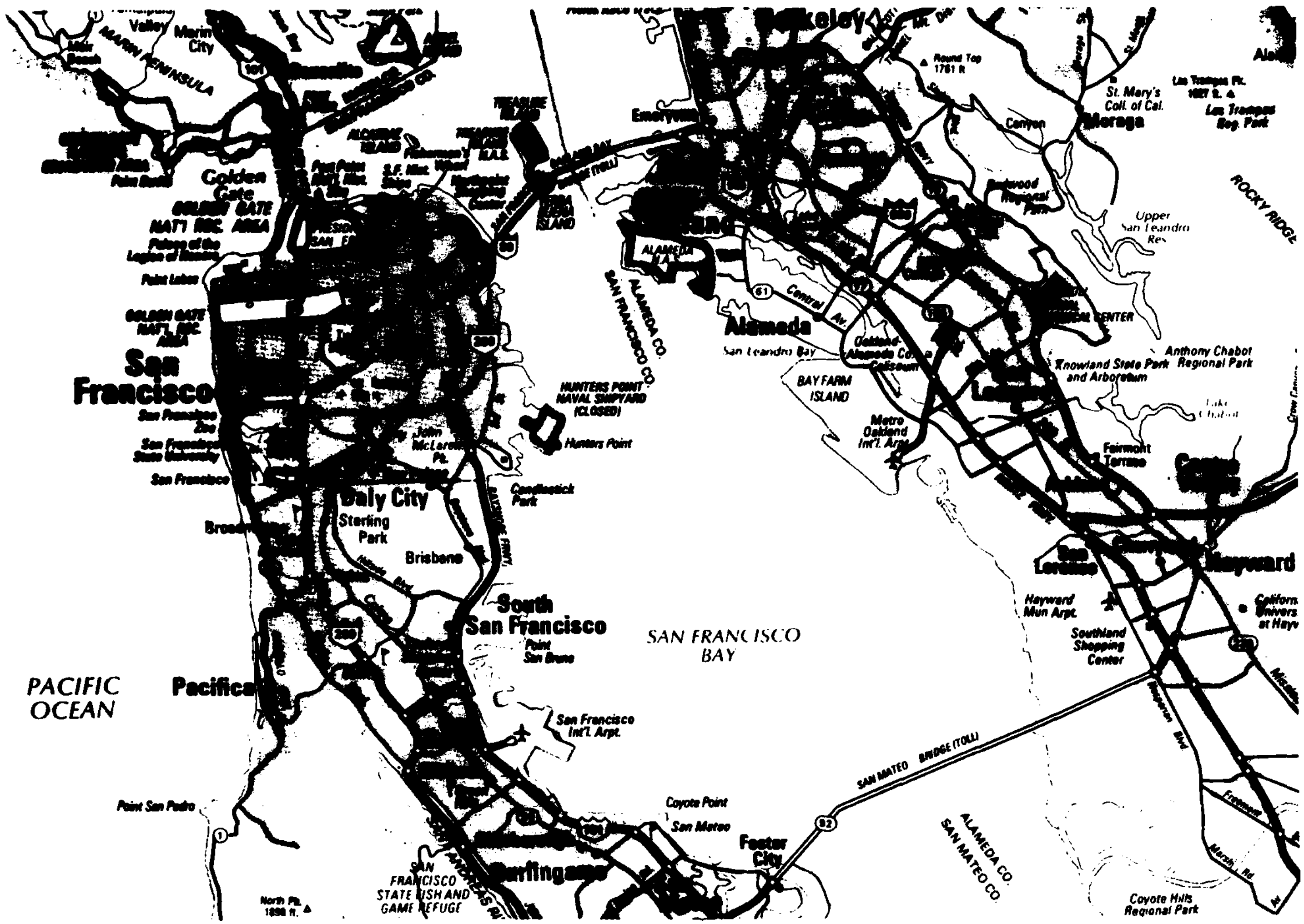

Figure 2. Relative location of NS, Treasure Island in the San Francisco Bay area.

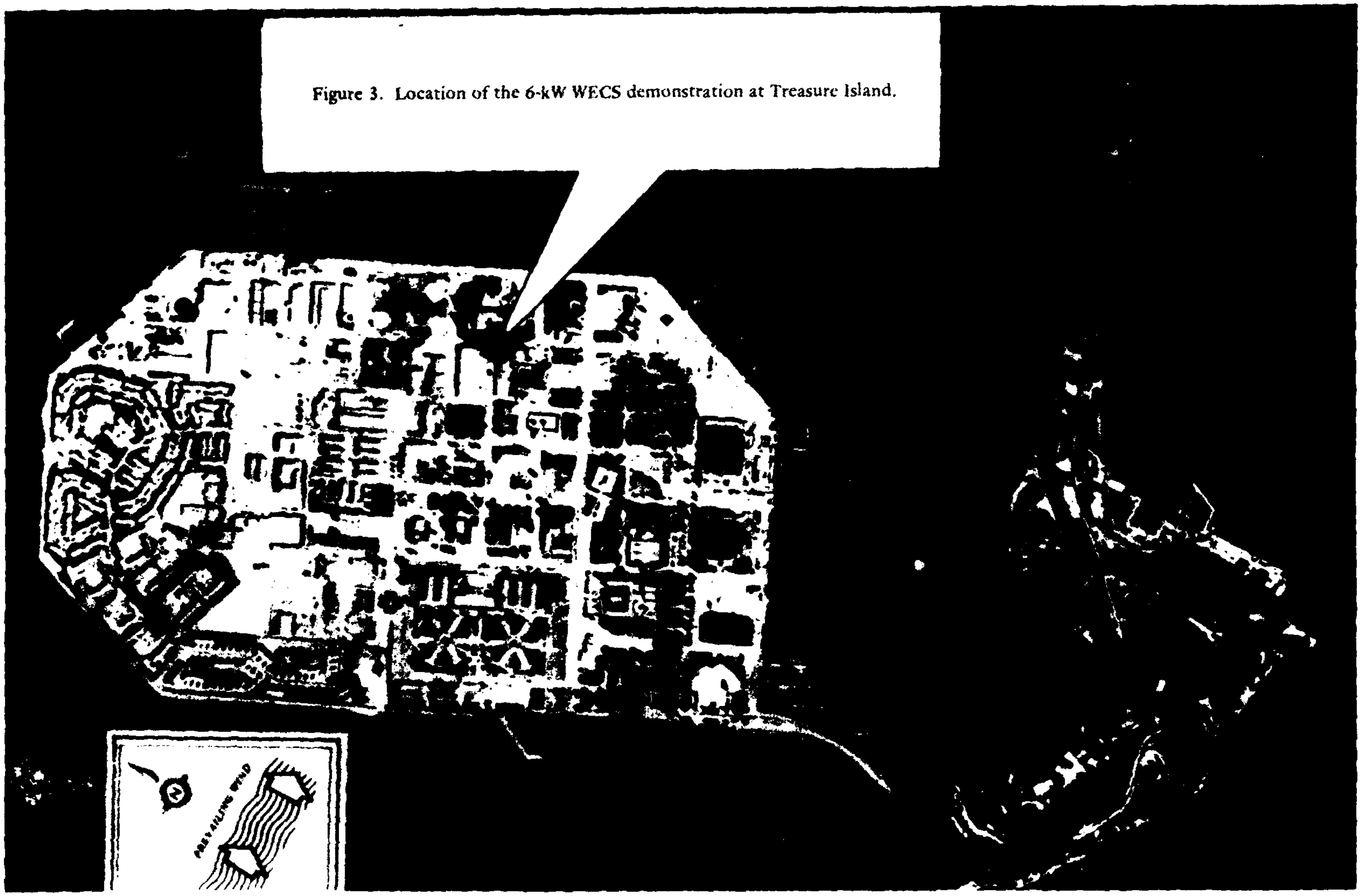

Figure 3. Location of the 6-kW WECS demonstration at Treasure Island.

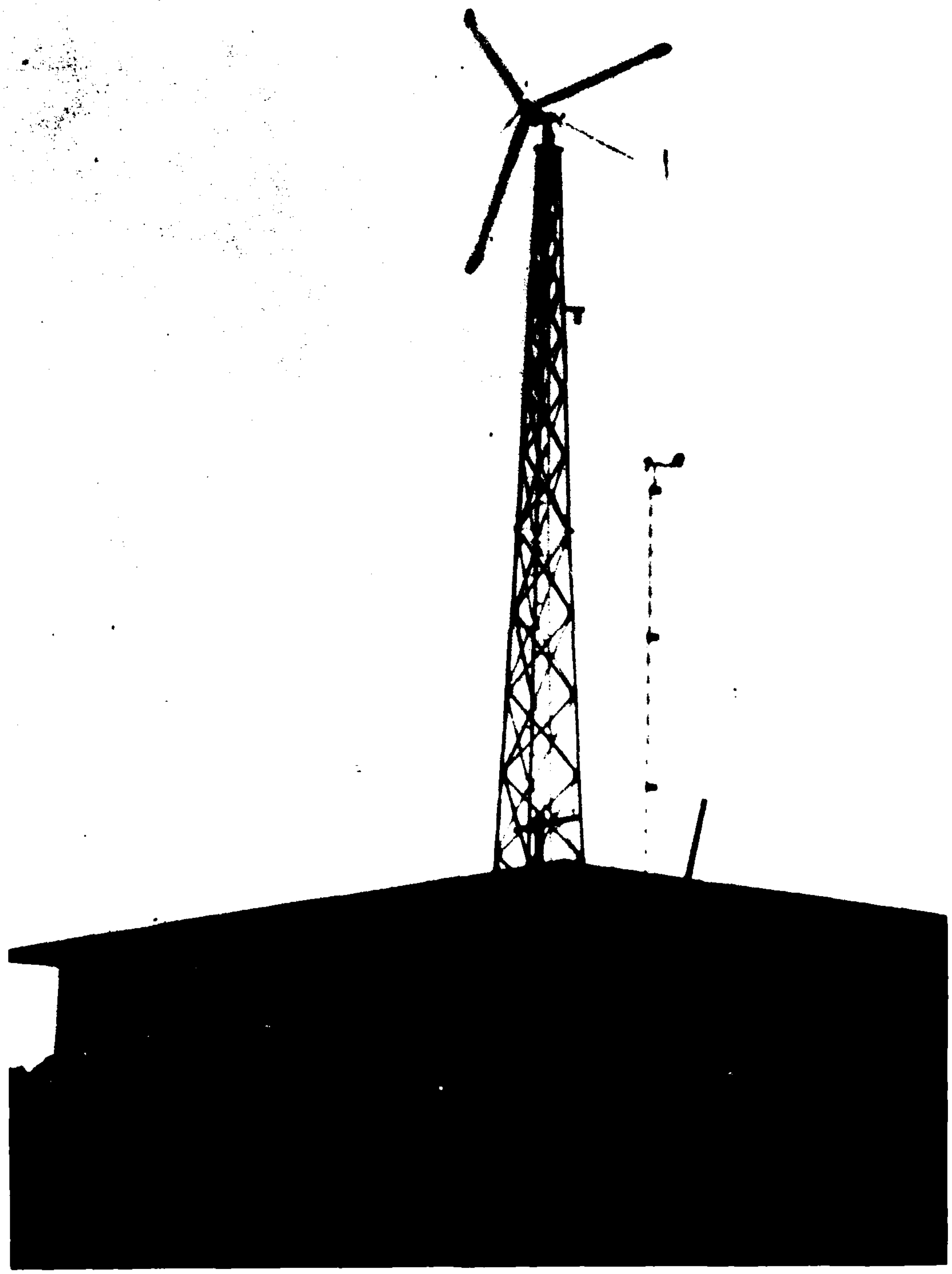

Figure 4. WECS installation at Treasure Island.

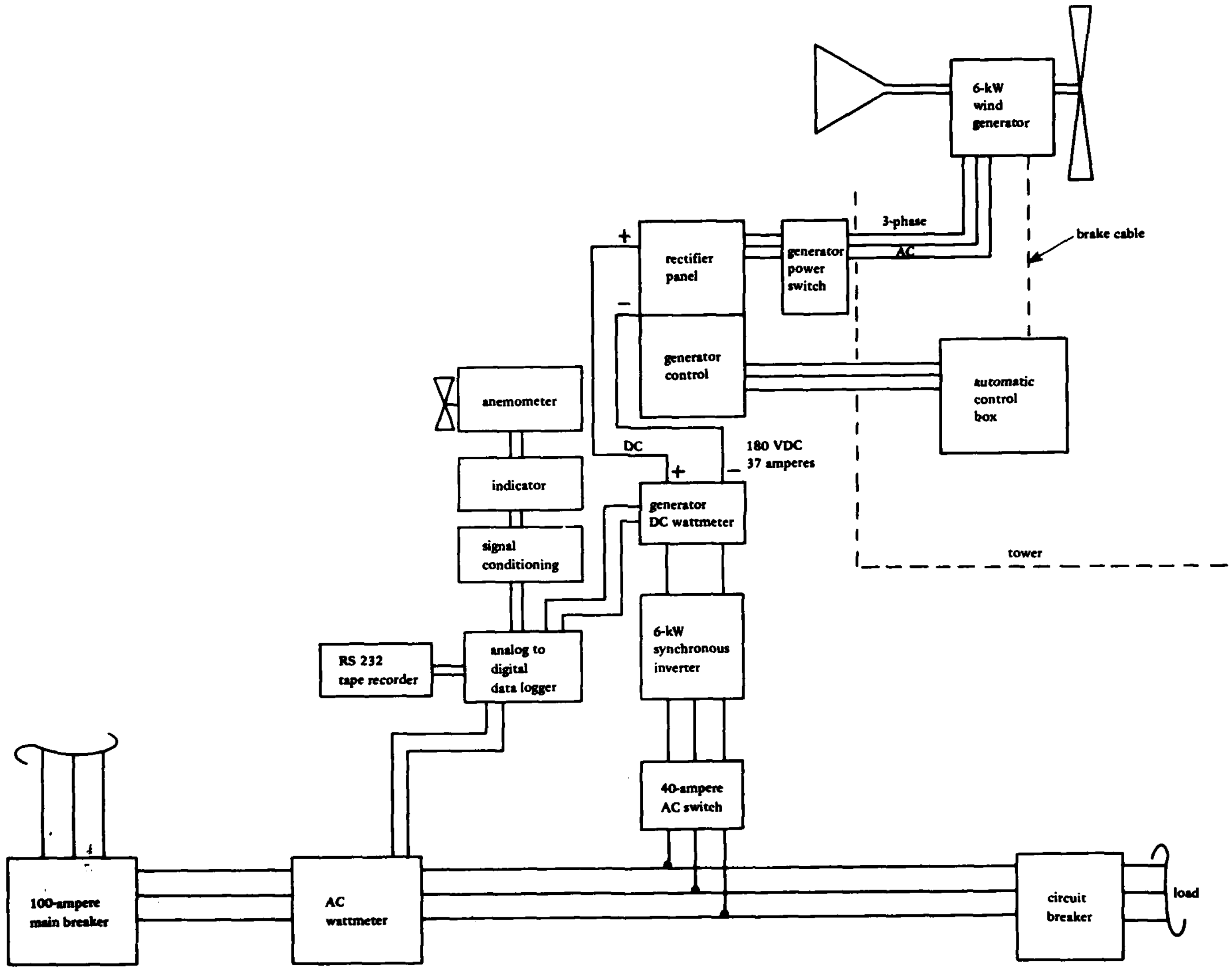

Figure 5. Wiring diagram for the wind generator and synchronous inverter at Treasure Island.

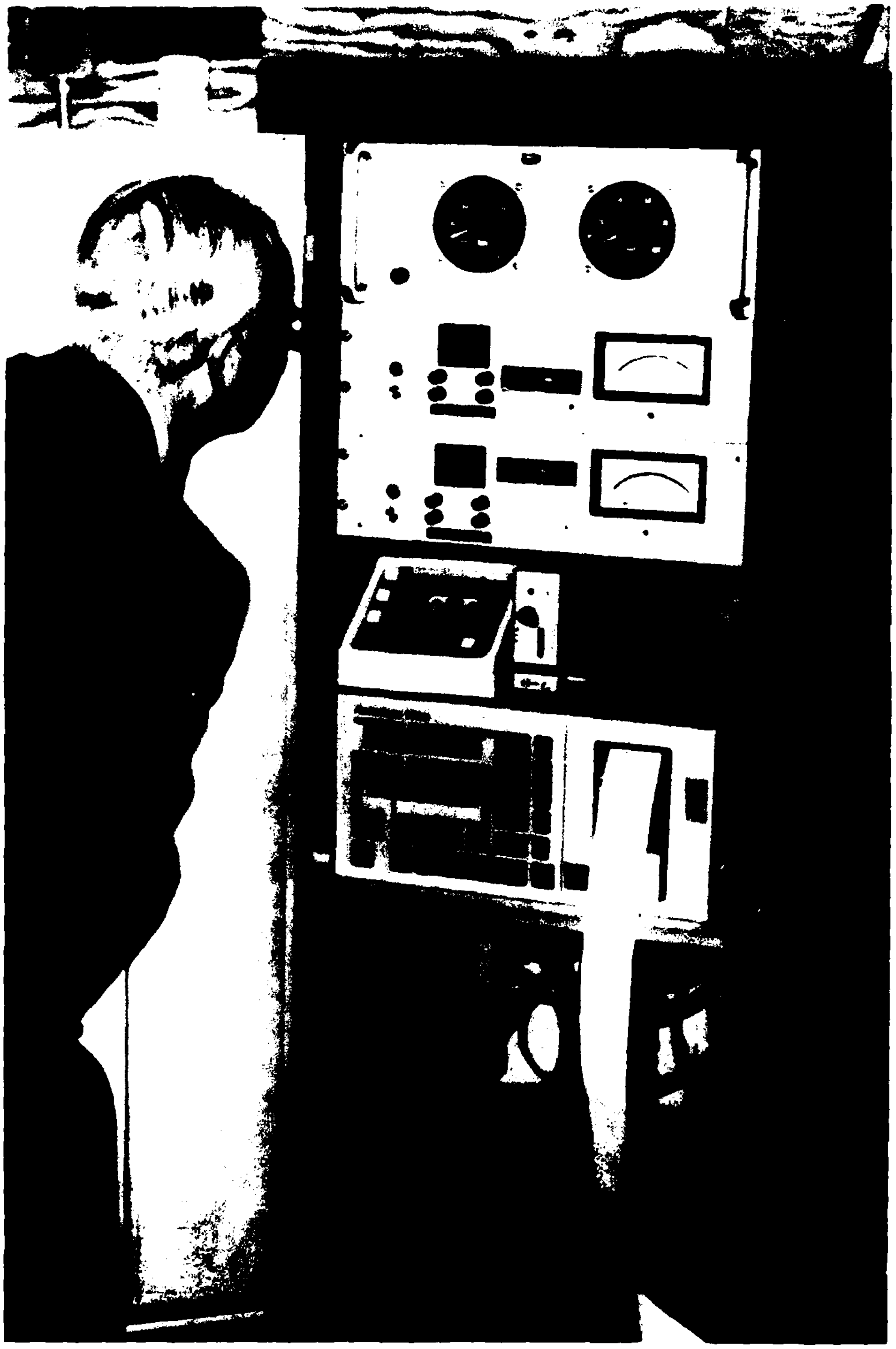

Figure 6. Instrument panel at Treasure Island for data collection.

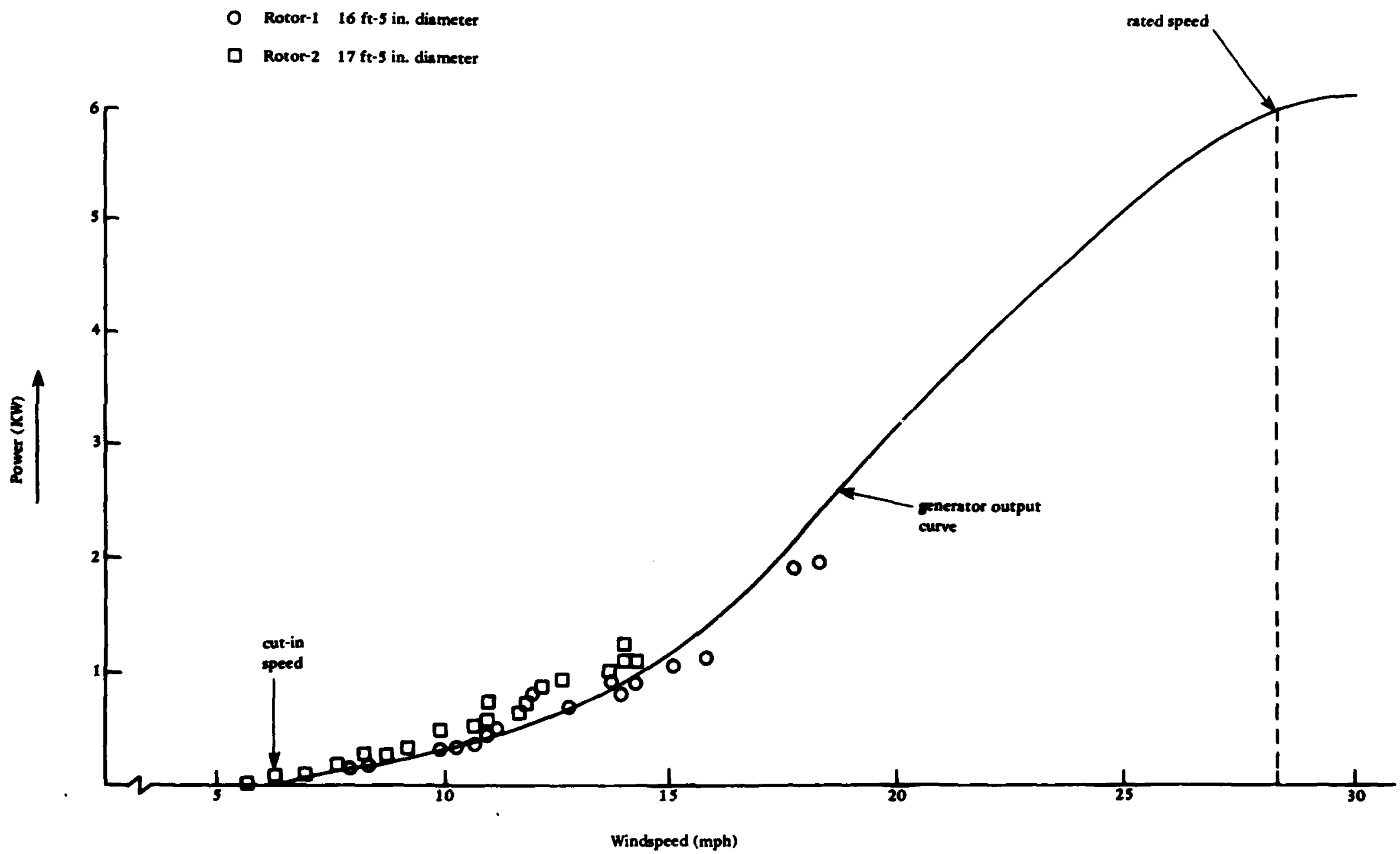

Figure 7. Performance curve for the 6-kW WECS with a synchronous inverter at NS, Treasure Island.

Inverter Performance

Windspeed	=	11.99 mph
AC power	=	0.72 kW
DC power	=	0.80 kW
Inverter efficiency	=	0.72/0.80 = 90%

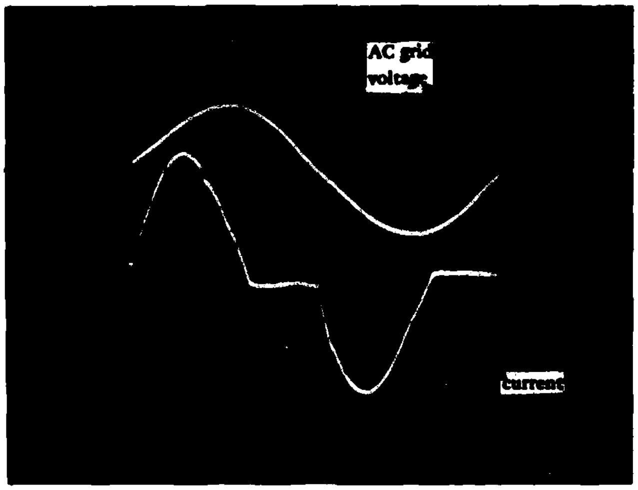

Figure 8. Synchronous inverter output waveforms at NS, Treasure Island.

Appendix A

LINE-COMMUTATED OR SYNCHRONOUS INVERSION OF DC POWER

For simplicity, consider a single-phase AC line connected to a source of DC power through a system of thyristors arranged in a bridge arrangement as shown in Figure A-1. The source of DC power in Figure A-1 is the output of a wind turbine-driven DC generator or an alternator with its output rectified.

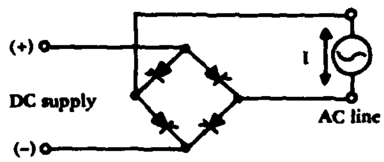

Figure A-1. Schematic of a synchronous inversion circuit.

Next, Figure A-2 shows alternate paths for current flow from the DC source to the AC line, depending upon the polarity of the AC line voltage.

Figure A-2. Two paths of power flow from wind-generated DC source to AC lines.

Further, the relative voltage and the wave form of the AC line and the DC source for the first path of power flow (Figure A-2(a)) is shown in Figure A-3 schematically. While Figure A-3 shows an arbitrary value of DC voltage, the actual magnitude can be any value from zero to the peak of the AC line. During the positive half cycle there are two distinct intervals, 1 and 2,

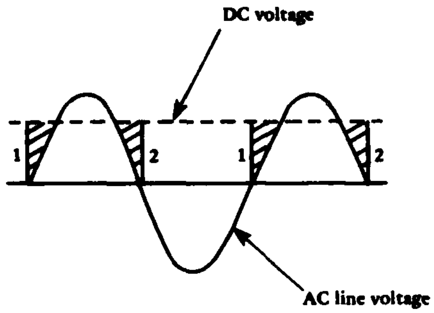

Figure A-3. A graphical description of DC source and AC line voltages.

where the DC source voltage is instantaneously more positive than the AC line voltage. Hence, current flows from the DC source to the line, and thus there is a flow of power to the line. During the negative half cycle of the AC line voltage, current does not oppose the line voltage, and power flow is in the opposite direction (i.e., from the AC line to the DC source).

The time intervals 1 and 2 have one significant difference as explained here. During interval 1, the difference between the AC and DC voltages is initially high and decreases to zero. This condition is useful when thyristors are employed as the power switches because it automatically reduces the current in the thyristors to zero, thus making it commutate naturally. In interval 2 the reverse occurs; that is, the voltage differential is zero initially and increases with time until it attains a large value at the end of the interval. For a thyristor to function properly during this interval, an independent or external means of commutating is generally required to switch it to the off-state. For thyristors, the commutating circuitry can be complex, and for this reason the conversion period is generally limited to interval 1 and the inverter is called a line-commutated inverter.

The circuitry of Figure A-2(a) and the DC power wave form depicted in Figure A-3 provide line current of a single polarity, and the power thus transferred to the AC line is DC. Hence, a circuitry of Figure A-2(b) is also needed for proper inversion of DC power from the wind generator. Figure A-4 shows the DC voltage and AC line wave form for a synchronous inverter technique based upon schematics of Figure A-2. The current flowing from the DC power source is truly AC and has the wave form given in Figure A-5. The discussion given here primarily applies to single-phase inverters, but the same principles can be extended to multiphase circuits.

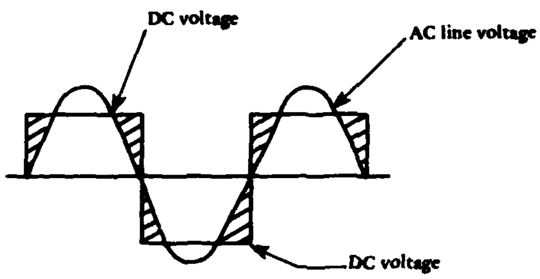

Figure A-4. A graphical description of synchronous inverter integration with the AC line.

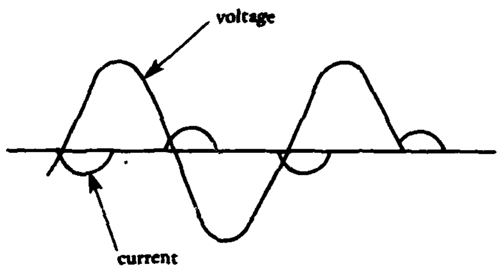

Figure A-5. Current and voltage profiles for the synchronous inversion method.

Appendix B

FIELD DATA LOG AND SYSTEM OPERATION RECORDS

Date	AC Wattmeter Reading	Average W-Hr/Day	DC Wattmeter Reading	Average W-Hr/Day	Average Inverter Efficiency	Comments
12-10-79	001436		027619			
12-17-79	001564	18	031310	527	0.03	
12-21-79	001616	13	032286	244	0.05	
12-22 & 12-23-79						Severe winds are being experienced at the site.
12-26-79	002342	145	044352	2,413	0.06	
1-7-80	002446	9	047486	261	0.03	
1-12 & 1-13-80						Severe winds prevailing. The Weather Bureau reports wind gusts from 40 to 70 mph at Angel Island approximately 3 miles northwest of Treasure Island in the San Francisco Bay.
1-14-80	002535	13	051645	594	0.02	The generator is found feathered out of the wind as a result of the machine's furling windspeed being exceeded. The unit is cranked back into the wind.
1-18-80						NCEL personnel made minor repairs and adjustments to the system. They also left instructions to use only one side of the cassette tape.

continued

Date	AC Wattmeter Reading	Average W-Hr/Day	DC Wattmeter Reading	Average W-Hr/Day	Average Inverter Efficiency	Comments
1-21-80	002588	8	054180	362	0.02	
1-28-80	002690	15	056704	361	0.04	
1-31-80						The cassette tape was changed and mailed to NCEL. Only one side was used - the tape lasted approximately two weeks.
2-4-80	002768	20	058520	454	0.04	
2-11-80	003440	96	069060	1,506	0.06	
2-15-80						The cassette tape was removed. Treasure Island experienced a rainstorm with winds from 10 to 20 mph.
2-20-80	003769	66	078508	1,050	0.06	
2-27-80	003885	17	081636	447	0.04	
3-3-80	003939	11	083102	283	0.04	The cassette tape was removed. One side only was used. The tape was shipped to NCEL.
3-8-80	004090	30	086876	755	0.04	
3-17-80	004231	16	090618	416	0.04	
3-24-80	004443	30	096547	847	0.04	
3-29 & 3-30-80						Strong winds are being experienced at the site.

continued

Date	AC Wattmeter Reading	Average W-Hr/Day	DC Wattmeter Reading	Average W-Hr/Day	Average Inverter Efficiency	Comments
3-31-80	004610	24	101301	679	0.04	The tape is changed.
4-7-80	004812	29	106995	813	0.04	
4-14-80	004912	14	109629	376	0.04	
4-21-80	005104	27	115127	785	0.03	
4-28-80	005297	28	120397	753	0.04	
5-5-80	005521	32	126738	906	0.04	
5-12-80	005784	38	135034	1,185	0.03	
5-19-80	005952	24	139670	662	0.04	
5-20-80	000000		000000			Both the AC and DC meters are set to "0".
5-20 - 5-23-80						NCEL personnel made adjustments and checked generator performance. The machine performs much more efficiently following the adjsutments. High winds up to 40 mph are being experienced at the site.
5-27-80	045734	6,533	056346	8,049	0.81	With the new setting, the machine cuts in at approximately 7 mph. Rotor rotation is sporadic between 7 and 10 mph. Above 10 mph, rotation is continuous.
6-2-80	078046	5,385	096658	6,719	0.80	
6-6-80	104471	6,606	129438	8,195	0.81	

Continued

Date	AC Wattmeter Reading	Average W-Hr/Day	DC Wattmeter Reading	Average W-Hr/Day	Average Inverter Efficiency	Comments
6-9-80	121907	5,812	151395	7,319	0.79	
6-16-80	169467	6,794	210794	8,486	0.80	
6-23-80	229359	8,556	286455	10,808	0.79	
6-30-80	263095	4,819	329560	6,158	0.78	
7-9-80	328410	7,257	413012	9,272	0.78	
7-14-80	365358	7,390	460514	9,500	0.78	
7-28-80	448355	5,928	567762	7,660	0.77	
8-4-80	486921	5,509	617673	7,130	0.77	
8-12-80	527973	5,132	670423	6,594	0.78	
8-18-80	558532	5,093	710195	6,629	0.77	
8-25-80	586478	3,992	746276	5,154	0.77	
9-2-80	623867	4,674	794931	6,082	0.77	
9-8-80	652585	4,803	832368	6,240	0.77	
9-15-80	692500	5,688	883452	7,298	0.78	
9-22-80	716114	3,373	914385	4,419	0.76	
9-29-80	743879	3,966	950628	5,178	0.77	
10-14-80	787305	2,895	007492	3,791	0.76	
10-21-80	798004	1,528	021575	2,012	0.76	
11-4-80	817550	1,396	047392	1,844	0.76	
11-6-80						The System was inspected and lubricated by NCEL personnel. No major maintenance problems were noted.

Continued

Date	AC Wattmeter Reading	Average W-Hr/Day	DC Wattmeter Reading	Average W-Hr/Day	Average Inverter Efficiency	Comments
11-12-80	823128	697	054780	924	0.75	
11-17-80	832015	1,777	066576	2,359	0.75	
11-25-80	843163	1,394	081050	1,809	0.77	
12-1-80	847861	783	087308	1,043	0.75	
12-8-80	890933	6,153	142024	7,817	0.79	
12-10-80	891792	430	143113	545	0.79	NCEL personnel changed the hub and blades on the turbine. The new blades are 6 inches longer than the previous ones. The unit was lubricated.
12-15-80	904857	2,613	160113	3,400	0.77	
12-22-80	911946	1,013	169333	1,317	0.77	
12-29-80	933544	3,085	197270	3,991	0.77	
1-5-81	962315	4,110	234430	5,309	0.77	
1-12-81	993273	4,423	274562	5,733	0.77	
1-20-81	001992	1,090	285738	1,397	0.78	
1-26-81	020211	3,037	309109	3,895	0.78	
2-2-81	058176	5,424	357163	6,865	0.79	
2-9-81	059909	248	359440	325	0.76	NCEL personnel installed a new tape recorder and checked the equipment. An oil retainer shield was left for Naval Station personnel to install on the

Continued

Date	AC Wattmeter Reading	Average W-Hr/Day	DC Wattmeter Reading	Average W-Hr/Day	Average Inverter Efficiency	Comments
						generator. Shortly after the repairs of the recording equipment were made, the paper tape jammed in the printer and neither the paper printout nor the tape recorder operated satisfactorily.
2-18-81	064532	514	365520	676	0.76	
2-23-81	084890	4,072	391373	5,171	0.79	
3-2-81	106382	3,070	418934	3,937	0.78	
3-10-81	114680	1,037	429811	1,360	0.76	
4-13-81	125721	325	473779	1,293	0.25	
4-22-81	128201	276	519602	5,091	0.05	
4-28-81	130493	382	552597	5,499	0.07	
5-4-81	130738	41	579076	4,413	0.009	
5-11-81	130913	25	604780	3,672	0.007	The machine cut in at a wind velocity of 9 mph and stayed on line at windspeeds of 9 mph and greater.
5-18-81	131656	106	640706	5,132	0.02	
5-19-91	000000		000000			NCEL personnel made extensive repairs of the equipment. A new tape recorder was installed. A broken wire was found at the generator and was repaired. Both the AC and DC meters were set to "0."

Continued

Date	AC Wattmeter Reading	Average W-Hr/Day	DC Wattmeter Reading	Average W-Hr/Day	Average Inverter Efficiency	Comments
5-20-81	002159	2,159	005504	5,504	0.39	
5-22-81	011263	4,552	022262	8,379	0.54	
5-26-81	023243	2,995	048214	6,488	0.46	
6-1-81	058246	5,834	111503	10,548	0.55	
6-7-81	087131	4,814	166776	9,212	0.52	The generator cut in at a windspeed of 9 mph. At this windspeed, the system generated approximately 0.4 kW of AC power.
6-15-81	116758	3,703	225025	7,281	0.51	A new cassette tape was installed.
6-22-81	127483	1,532	256465	4,491	0.34	
6-30-81	172322	5,605	339688	10,403	0.54	

Appendix C

WECS PERFORMANCE DATA FOR ROTOR-1 AND ROTOR-2

Table C-1. WECS Performance Data for Rotor-1.

(Running average data with 1 hour averaging period)

Date	Time	Wind Speed (mph)	Ambient Temperature (°F)	Available Power In Wind (kW)	DC Generator Output (kW)	AC Inverter Output (kW)	Efficiency		
							Generator (%)	Inverter (%)	System (%)
7 Jun 1980	1700	14.13	69.3	3.075	0.606	0.461	19.7	76.1	15.0
	1800	15.68	67.6	4.202	0.789	0.605	18.8	76.7	14.4
	1900	12.71	64.03	2.238	0.591	0.448	26.4	75.8	20.0
	2000	11.09	56.9	1.487	0.374	0.281	25.2	75.1	18.9
8 Jun 1980	1200	12.87	59.7	2.324	0.462	0.343	19.9	74.2	14.8
	1300	14.75	60.7	3.498	0.555	0.415	15.9	74.8	11.9
	1400	15.70	61.6	4.219	0.794	0.605	18.8	76.2	14.3
	1500	14.29	64.3	3.181	0.668	0.505	21.0	75.6	15.9
	1600	16.35	68.0	4.765	1.017	0.794	21.3	78.1	16.6
	1700	17.68	67.8	6.024	1.122	0.879	18.6	78.3	14.6
10-Jun 1980	1400	20.32	57.5	9.146	2.013	1.683	22.0	83.6	18.4
	1500	20.59	59.7	9.516	1.886	1.558	19.8	82.6	16.4
	1700	18.09	65.08	6.453	1.661	1.335	25.7	80.37	20.7
15 Jun 1980	1000	6.35	57.7	0.2791	0.0510	0.0325	18.3	63.8	11.7
	1100	7.90	58.95	0.5375	0.117	0.0825	21.8	70.5	15.4
	1200	11.63	59.4	1.715	0.396	0.290	23.1	63.9	14.8
	1300	9.78	62.3	1.020	0.239	0.176	23.4	73.6	17.2
	1400	10.92	62.9	1.419	0.330	0.240	23.3	72.70	16.9
	1500	14.65	64.7	3.428	0.713	0.538	20.8	75.5	15.7
	1600	13.28	71.3	2.553	0.513	0.379	20.1	73.9	14.9
	1700	13.69	71.61	2.797	0.618	0.465	22.1	75.2	16.6
	1800	11.70	70.9	1.746	0.360	0.265	20.7	73.6	15.2
	1900	10.55	66.3	1.280	0.306	0.225	23.9	73.5	17.6

Continued

Table C-1. Continued

Date	Time	Wind Speed (mph)	Ambient Temperature (°F)	Available Power In Wind (kW)	DC Generator Output (kW)	AC Inverter Output (kW)	Efficiency		
							Generator (%)	Inverter (%)	System (%)
	2000	8.22	58.9	0.6055	0.173	0.126	28.6	72.8	20.8
	2100	8.61	52.8	0.6958	0.156	0.115	22.4	73.7	16.5
	2200	9.33	53.3	0.8853	0.225	0.164	25.4	72.9	18.5
2 Dec 1980	0200	6.75	51.36	0.3368	0.0540	0.038	16.03	70.37	11.28
	0300	8.35	51.70	0.6372	0.171	0.115	26.84	67.25	18.05
	0400	7.46	51.77	0.4543	0.132	0.0863	29.05	65.38	19.00
	0500	8.53	51.72	0.6792	0.194	0.130	28.56	67.01	19.14
	0700	8.08	52.58	0.5764	0.167	0.113	28.97	67.37	19.52
	0900	9.58	52.07	0.9616	0.300	0.221	31.20	73.75	23.00
	1000	10.67	52.04	1.329	0.431	0.325	32.43	75.49	24.48
	1100	11.12	53.17	1.501	0.470	0.356	31.32	75.83	23.75
	1200	12.72	54.41	2.241	0.674	0.523	30.08	77.65	23.35
	1300	12.33	55.75	2.035	0.678	0.528	33.32	77.88	25.95
	1400	13.52	57.82	2.673	0.942	0.749	35.24	79.51	28.02
	1600	14.00	58.51	2.964	1.031	0.826	34.79	80.16	27.87
	1700	15.85	57.45	4.310	1.173	0.933	27.22	79.50	21.65
	2000	15.10	54.91	3.745	1.080	0.841	28.84	77.89	22.46
	2100	14.20	55.13	3.113	0.911	0.700	29.26	76.84	22.49
	2200	10.41	54.75	1.227	0.369	0.266	30.07	72.15	21.68
	2300	10.76	54.99	1.355	0.461	0.343	34.03	74.30	25.28
	2400	13.97	55.98	2.959	0.842	0.641	28.46	76.16	21.67
3 Dec 1980	1600	17.80	51.26	6.178	1.947	1.59	31.52	81.66	25.74
	1700	18.38	50.21	6.816	2.007	1.633	29.45	81.37	23.95

Table C-2. Wecs Performance Data for Rotor-2.

(Running average data with 1-hour averaging period)

Date	Time	Wind Speed (mph)	Ambient Temperature (°F)	Available Power In Wind (kW)	DC Generator Output (kW)	AC Inverter Output (kW)	Efficiency		
							Generator (%)	Inverter (%)	System (%)
27 Dec 1980	0938	12.18	47.47	2.245	0.812	0.620	36.16	76.35	27.61
	1038	11.92	48.62	2.100	0.729	0.561	34.72	76.95	26.71
	1138	11.76	49.66	2.012	0.654	0.501	32.51	76.64	24.91
	1238	13.78	50.08	3.235	0.999	0.775	30.88	77.58	23.96
	1438	14.30	49.40	3.620	1.043	0.8038	28.81	77.06	22.20
	1738	10.79	48.02	1.559	0.537	0.403	34.44	75.05	25.85
	1938	9.25	46.99	0.9844	0.338	0.248	34.34	73.37	25.19
30 Dec 1980	1538	12.72	50.78	2.541	0.9525	0.7525	37.49	79.00	29.61
	1638	13.92	49.12	3.341	1.2525	0.975	37.49	77.84	29.18
2 Jan 1981	1438	9.86	50.03	1.185	0.497	0.380	41.93	76.46	32.07
	1638	12.01	45.83	2.159	0.714	0.543	33.07	75.98	25.15
	1838	10.98	43.74	1.6571	0.569	0.428	34.34	75.13	25.83
	2038	19.21	42.97	1.3344	0.437	0.325	32.75	74.37	24.36
	2238	8.95	43.06	0.8987	0.302	0.220	33.60	72.85	24.48
	2338	9.99	42.65	1.2508	0.506	0.375	40.45	74.11	29.98
3 Jan 1981	0538	8.87	40.09	0.8800	0.384	0.281	43.64	73.24	31.93
	0738	7.71	39.93	0.5781	0.191	0.136	33.04	71.20	23.53
	0938	7.97	41.88	0.6361	0.197	0.144	30.97	72.97	22.63
	1138	10.84	44.68	1.5916	0.561	0.421	35.25	75.10	26.45
	1238	11.43	45.38	1.8633	0.630	0.473	33.81	75.00	25.39
	1438	11.48	46.25	1.8846	0.584	0.439	31.00	75.13	23.29
	1638	11.81	44.77	2.058	0.695	0.529	33.77	76.17	25.73
	2038	8.34	41.98	0.7287	0.215	0.160	29.50	74.42	21.96

Continued

Table C-2. Continued

Date	Time	Wind Speed (mph)	Ambient Temperature (°F)	Available Power In Wind (kW)	DC Generator Output (kW)	AC Inverter Output (kW)	Efficiency		
							Generator (%)	Inverter (%)	System (%)
	2338	6.36	40.90	0.3239	0.075	0.054	23.16	71.67	16.60
4 Jan 1981	0038	7.14	40.80	0.4583	0.116	0.0813	25.31	70.04	17.73
	1838	6.40	43.95	0.3280	0.120	0.0875	36.58	72.92	26.68

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NAVSHIPYD Code 202.4, Long Beach CA; Code 202.5 (Library) Puget Sound, Bremerton WA; Code 380, Portsmouth, VA; Code 382.3, Pearl Harbor, HI; Code 400, Puget Sound; Code 440 Portsmouth NH; Code 440, Norfolk; Code 440, Puget Sound, Bremerton WA; Code 440.1 (R. Schwinck), Long Beach, CA; Code 444, (Wgt Handling Engr) Philadelphia, PA; Code 453 (Util. Supr), Vallejo CA; Code 457 (Maint. Supr.) Mare Island, Vallejo CA; LTJG R. Lloyd, Vallejo CA; Library, Portsmouth NH; PW Dept, Long Beach, CA; PWD (Code 420) Dir Portsmouth, VA; PWD (Code 450-HD) Portsmouth, VA; PWD (Code 453-HD) SHPO 03, Portsmouth, VA; PWD - Asst PWO, Code 410, Vallejo, CA; PWD - Utilities Supt, Code 903, Long Beach, CA; PWO, Bremerton, WA; PWO, Mare Is.; PWO, Portsmouth NH; PWO, Puget Sound; Tech Library, Vallejo, CA; Utilities & Energy Cons. Mgr Code 108.1, Pearl Harbor, HI
NAVSTA Adak, AK; CO, Brooklyn NY; Code 16P, Keflavik, Iceland; Code 4, 12 Marine Corps Dist, Treasure Is., San Francisco CA; Dir Engr Div, PWD, Mayport FL; Dir Mech Engr 37WC93 Norfolk, VA; Engr. Dir., Rota Spain; Long Beach, CA; Maint. Cont. Div., Guantanamo Bay Cuba; Maint. Control Div., Adak; Maint. Div. Dir/Code 531, Rodman Panama Canal; Maintenance Div., Rota, Spain; PWD - Engr Dept, Adak, AK; PWD - Engr Div, Midway Is.; PWD - Engr. Div, Keflavik; PWD, Utilities Div., Guantanamo Bay Cuba; PWO, Adak, AK; PWO, Brooklyn NY; PWO, Keflavik Iceland; PWO, Mayport FL; SCE, Guam; SCE, Pearl Harbor HI; SCE, San Diego CA; Utilities Engr Off. Rota Spain
NAVSUBASE ENS S. Dove, Groton, CT; PWO
NAVSUPPACT CO, Naples, Italy; PWO Naples Italy; PWO, New Orleans LA; SCE, Long Beach CA; SCE, Mare Is., Vallejo CA
NAVSUPPFAC PWD - Maint. Control Div, Thurmont, MD; PWO, Thurmont MD
NAVSUPPO PWO, La Maddalena, Italy; Security Offr, Sardinia
NAVSURFWPNCEN Commander, Dahlgren, VA; PWO, White Oak, Silver Spring, MD; Security Offr, Silver Spring MD
NAVTECHTRACEN Code N213 Orlando FL; SCE, Pensacola FL
NAVTELCOMMCOM Code 53, Washington, DC
NAVUSEAWARENGSTA Engr. Div. (Code 083) Keyport, WA; PWO, Keyport WA
NAVWARCOL Dir. of Facil., Newport RI
NAVWPNCEN Code 24 (Dir Safe & Sec) China Lake, CA; Code 2636 China Lake; Code 266, China Lake, CA; Code 26605 China Lake CA; Code 3803 China Lake, CA; Code 623 China Lake CA; PWO (Code 266) China Lake, CA; ROICC (Code 702), China Lake CA; ROICC, Code 7002, China Lake CA
NAVWPNEVALFAC Technical Library, Albuquerque NM
NAVWPNSTA (Clebak) Colts Neck, NJ; Code 092A, Seal Beach, CA
NAVWPNSTA PW Office Yorktown, VA
NAVWPNSTA PWD - Maint. Control Div., Concord, CA; PWD - Supr Gen Engr, Seal Beach, CA; PWO Colts Neck, NJ; PWO, Charleston, SC; PWO, Seal Beach CA
NAVWPNSUPPCEN Code 09 Crane IN; ENS J. Wyman, Crane IN
NAVY PAO CENTER Directory, San Diego, CA
NCTC Const. Elec. School, Port Hueneme, CA
NSC SCE, Charleston, SC
NCBC CO, Gulfport MS; Code 10 Davisville, RI; Code 15, Port Hueneme CA; Code 155, Port Hueneme CA; Code 156, Port Hueneme, CA; Code 25111 Port Hueneme, CA; Code 430 (PW Engrng) Gulfport, MS; Code 470.2, Gulfport, MS; NEESA Code 252 (P Winters) Port Hueneme, CA; PWO (Code 80) Port Hueneme, CA; PWO - Code 84, Port Hueneme, CA; PWO Gulfport, MS; PWO, Davisville RI; PWO, Gulfport, MS; Port Hueneme CA
NCBU 416 OIC, Alameda CA
NCR 20, Code R31 Gulfport, MS; 20, Code R70
NMCB 1, CO; 1, Code S3E; 133, CO; 3, CO; 4, CO; 5, CO; 62, CO; 74, ENS Vesely; FIVE, Operations Dept; THREE, Operations Off.
NOAA (Dr. T. Mc Guinness) Rockville, MD; Library Rockville, MD
NRL Code 5800 Washington, DC; Code 6620 (Faraday), Wash., DC
NSC Code 09A Security Offr, Norfolk, VA; Code 54.1 Norfolk, VA; Code 703 (J. Gammon) Pearl Harbor, HI; SCE (Code 70), Oakland CA; SCE Norfolk, VA; SCE, Guam
NSD PWD - Engr Div, Guam; SCE, Subic Bay, R.P.
NSWSES Code 0150 Port Hueneme, CA
NTC SCE, San Diego CA
NTIS Lehmann, Springfield, VA
NUSC Code 131 New London, CT; Code 3009 (CDR O. Porter) Newport, RI; Code 4111 (R B MacDonald) New London CT; Code 4123 New London, CT; Code EA123 (R.S. Munn), New London CT; Code SB 331 (Brown), Newport RI; PWO AUTEC West Palm Bch Det. West Palm Beach, FL; PWO New London, CT; PWO Newport, RI; SB322 (Tucker), Newport RI
OFFICE SECRETARY OF DEFENSE DASD (I&H) IC Pentagon; OASD (MRA&L) Dir. of Energy, Pentagon, Washington, DC

ONR Code 221. Arlington VA; Code 700F Arlington VA; LCDR Williams. Boston. MA; Nelson. Arlington. VA
PACMISRANFAC HI Area Bkg Sands. PWO Kekaha. Kauai. HI
PERRY OCEAN ENG R. Pellen. Riviera Beach. FL
PHIBCB 1 P&E. San Diego. CA
PMTC Code 3331 (S. Opatowsky) Point Mugu. CA; Pat. Counsel. Point Mugu CA; Security Offr. Point Mugu CA
PWC CO Norfolk. VA; CO Yokosuka. Japan; CO. (Code 10). Oakland. CA; CO. Great Lakes IL; CO. Pearl Harbor HI; CO. San Diego CA; CO. Subic Bay. R.P.; Code 10. Great Lakes. IL; Code 101. San Diego. CA; Code 105 Oakland. CA; Code 110. Great Lakes. IL; Code 110. Oakland. CA; Code 120. Oakland CA; Code 120. San Diego CA; Code 120C. (Library) San Diego. CA; Code 154. Great Lakes. IL; Code 200 (H. Koubenec). Great Lakes IL; Code 200. Great Lakes IL; Code 240. Subic Bay. R.P.; Code 400. Great Lakes. IL; Commanding Officer. Subic Bay; Code 400. Pearl Harbor. HI; Code 400. San Diego. CA; Code 420. Great Lakes. IL; Code 420. Oakland. CA; Code 420. Pensacola. FL; Code 420. San Diego. CA; Code 424. Norfolk. VA; Code 500 Norfolk. VA; Code 500. Great Lakes. IL; Code 500. Oakland. CA; Code 505A Oakland. CA; Code 600. Great Lakes. IL; Code 610. San Diego Ca; Code 700. Great Lakes. IL; Code 800. San Diego. CA; Library. Pensacola. FL; Library. Guam; Library. Norfolk. VA; Library. Subic Bay. R.P.; Library. Pearl Harbor. HI; Maint. Control Dept (R. Fujii) Pearl Harbor. HI; Production Officer. Norfolk. VA; Util Dept (R Pascua) Pearl Harbor. HI
SPCC PWD - Maint. Control Div. Mechanicsburg. PA; PWO (Code 120) Mechanicsburg PA
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